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# Overview of the Jefferson Lab IR FEL Program

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**Abstract**

Jefferson Lab (formerly known as CEBAF) is building a kilowatt-level free-electron laser operating in the mid-infrared to study technologies required for high average power operation. The design of the driver accelerator, its subsystems, and the wiggler and optical cavity will be described. We also present estimates of the output power, electron beam quality, and beam stability during energy recovery. Finally, the status of the project will be reviewed.

## 1. Introduction

Thomas Jefferson National Accelerator Facility (Jefferson Lab) has recently received funding from the U.S. Department of the Navy, U.S. DOE, the Commonwealth of Virginia, and Industry to demonstrate high average power generation in a free-electron laser. The goal of the program is technology and application development of laser sources (on the order of 100 kW or higher) with high efficiency and low cost per photon, for defense and industrial applications. The first step in the program is to demonstrate kilowatt level average power in a FEL and to test out the technologies and physics required to scale the system to higher powers. Important technologies for high average power include energy recovery, superconducting RF (SRF) accelerators, multipass acceleration, and high-current injectors. We must also understand the physics of electron beam halo formation and emittance preservation.

The design wavelength for the Jefferson Lab FEL was chosen to be 3 μm with the plan to upgrade later to 1–2 μm and eventually 0.2 μm. Members of the Laser Processing Consortium, a group of industrial and university collaborators interested in exploring the potential uses of high power FELs in micromachining, polymer, and metal surface processing, plan to use the FEL at several wavelengths in the mid-infrared [1].

The accelerator and FEL hardware is scheduled to be complete and installed by Sept. 1997. This ambitious schedule necessitates the use of existing technology wherever possible. Experience, infrastructure, and designs developed in the construction and commissioning of the 4 GeV machine at Jefferson Lab and other accelerators will be used to reduce design and construction time.

## 2. Accelerator Design

The layout for the infrared demonstration FEL (IR Demo FEL) is shown in figure 1. The electrons are produced in a 350–500 kV DC photocathode gun [2] and accelerated to 10 MeV in a superconducting accelerating unit with 1 meter of active length. The electrons are then bunched slightly before acceleration in an SRF cryomodule up to an energy of 42 MeV. In order to minimize emittance-growth effects and to accelerate the commissioning process, the FEL is placed at the exit of the linac. The electron beam is deflected around two cavity mirrors in two magnetic chicanes with a path-length dispersion ($M_{56}$) of 30 cm. After the FEL, the beam can be recirculated for energy recovery and dumped at the injection energy of 10 MeV. The recirculation loop is based on the isochronous achromat used in the Bates accelerator [3] and is similar to the design presented in previous work [4]. Unlike the design in [4] however, this lattice has been designed with an energy acceptance of 6%.

Calculations indicate that emittance growth in the Bates 180° bend might be significant [5]. This growth poses problems for any future two-pass system. In order to predict future performance, we plan to carefully measure the emittance before and after the Bates bend and compare with calculations.

Table 1 summarizes the laser and accelerator parameters. We estimate, using parameterizations of the FEL equations [6], that the power output at 3 μm for these parameters should be 980 W with a small signal gain of 46%. Simulations of the entire acceleration process from the photocathode to the FEL using the code PARMELA predict transverse and longitudinal emittances approximately half of those listed in table 1. If this beam performance is obtained and an rms wiggler parameter $K$ of 1.0 is used, it should be straightforward to lase at the third harmonic (at 1.35 μm), with approximately one third the power at the

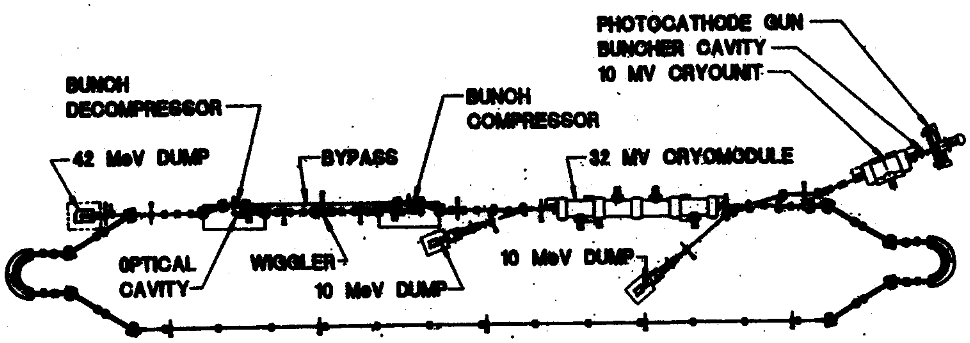


Figure 1. Layout of the IR Demo FEL. The electron beam is injected into the accelerator at 10 MeV, is accelerated to 42 MeV, goes through the FEL, is recirculated back to the linac, and is decelerated back down to 10 MeV and dumped.

fundamental and a gain of 48%. For the emittances in Table 1, the third harmonic gain is approximately 14%.

Table 1. Parameters for the IR Demo FEL

| | |
|---|---|
| <u>Wiggler</u> | |
| Period | 2.7 cm |
| Number of periods | 40 |
| rms $K^2$ | 0.5 (optionally 1.0) |
| Phase noise | <5° rms |
| Trajectory wander | <±100 µm&<±500 µrad |
| <u>Optical Cavity</u> | |
| Length | 8.0105 m |
| Rayleigh range | 40 cm |
| Total losses | 5% |
| Extraneous losses | 1–2% |
| Mode rotation vs. mirror tilt | 50X |
| <u>Electron Beam</u> | |
| Kinetic Energy | 42 MeV |
| Average current | 5 mA |
| Repetition rate | 37.425 MHz |
| Charge per bunch | 135 pC |
| Norm. transverse emittance | 13 mm-mrad |
| Longitudinal emittance | 50 keV-deg |
| ß function at wiggler center | 50 cm |
| Energy spread ($\sigma_\gamma/\gamma$) | 0.20% |
| Peak current | 50 A |
| Bunch length (rms) | 1 psec |

## 3. Wiggler and Resonator

The wiggler design chosen has a 2.7 cm period with a fixed rms $K^2$ of 0.5 and 40 effective wiggler periods. The wiggler is being constructed by STI Optronics (Bellevue, WA) and is based on the design of the U27 undulator at Argonne National Laboratory [7]. That undulator achieves an rms $K^2$ of 0.5 for a gap of 14.4 mm and an rms $K^2$ of 1.0 at a gap of 11.8 mm. The latter configuration is useful for increased power at long wavelengths and for harmonic lasing. The phase jitter in the wiggler was specified to be less than 5° so that the third-harmonic gain would not be significantly degraded by the wiggler.

In order to save time and to maximize the output coupling efficiency, we chose a simple, nearly concentric resonator with dielectric reflective mirror coatings. Such a cavity is quite sensitive to changes in mirror steering and radius of curvature. Calculations of the mirror distortion due to absorbed power indicate that sapphire substrates are adequate to maintain mirror distortion at acceptable levels. If necessary, the mirror mounts can be modified to permit active angle stabilization.

## 4. Energy stability

As noted previously [8] recirculating, energy-recovery accelerators exhibit instabilities which arise from fluctuations of the cavity fields. We carried out stability analysis for small perturbations from equilibrium and found the threshold current for the IR Demo FEL to be 1 mA. At 5 mA an RF feedback gain of 10 is necessary for frequencies less than 1 kHz. The system simulation model includes real-world effects such as microphonics, startup transients, and coupler mismatches. The gradient and phase stability exhibited in the simulations is better than 0.01% and 0.1° respectively for reasonable operating conditions.

## 5. Commissioning

During initial commissioning, the electron beam is dumped at full energy in a straight-ahead beam dump. The current will be limited to approximately 625 µA due to the RF power available in the accelerating module. The gain with this much current is only about 15%. This is sufficiently low that the optical cavity must have a higher Q and the electron beam must be set up very accurately to ensure lasing. We have looked at the sensitivity of the gain to variations in parameters and found that the most critical parameters in the initial setup are the angular separation between the optical mode and the electron beam, and the peak current. A scanning coherent-optical-transition-radiation interferometer [9] will be used to characterize and optimize the electron bunch length and shape at the wiggler entrance. Since photon detectors are much more sensitive at near-infrared wavelengths, and since the spectrum of the harmonic is more sensitive to the angle between the electron beam and the optical mode, we plan to use the third-harmonic spectrum to optimize this angle.

### 6. Injector

The injector's photocathode gun is presently being commissioned. Commissioning was initially delayed by field-emission-induced vacuum leaks in the high-voltage ceramics, occurring at voltages higher than 300 kV. We are presently pursuing several approaches to solving this problem and expect to have ceramics capable of withstanding at least 400 kV by the end of 1996. The gun is presently (Aug. 1996) being commissioned at 250 kV. The results of the beam property measurements from the gun will be compared to PARMELA simulations so that future gun operation can be predicted using numerical simulations.

### 7. Schedule

A kilowatt-class mid-infrared free-electron laser is being assembled at Jefferson Lab. The building is under construction and should have initial occupancy by April 1997. The injector's photocathode gun is presently being commissioned. The injector should have demonstrated high current (5 mA), 10 MeV beam by the summer of 1997. All other systems such as magnets, vacuum, RF, cryogenics, optics, and instrumentation and control are on schedule. The critical technology for this device is the injector and we are focusing on its development.

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**KEYWORD(S)**

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|---|---|---|
| ☐ Accelerator Physics | ☐ Diagnostics | ☐ Magnets |
| ☐ Arc | ☐ Environment, QA | ☐ Nuclear Physics |
| ☒ Beam Dynamics | ☐ Experimental Equipment | ☒ RF |
| ☒ Beam Transport | ☐ Extraction | ☐ Safety and Health Physics |
| ☐ BSY | ☐ Failure Mode/Tests | ☐ Schedule |
| ☐ Civil Construction | ☒ Free Electron Laser (FEL) | ☐ SRF |
| ☒ Commissioning | ☐ Front End | ☐ Test Results |
| ☐ Controls | ☒ Injector | ☐ Vacuum |
| ☐ Cost | ☐ Installation | ☐ Other |
| ☐ Cryogenics | ☐ Integration | |
| ☐ DC Power | ☐ Linac | |


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Jefferson Lab (formerly known as CEBAF) is building a kilowatt-level free-electron laser operating in the mid-infrared to study technologies required for high average power operation. The design of the driver accelerator, its subsystems, and the wiggler and optical cavity will be described. We also present estimates of the output power, electron beam quality, and beam stability during energy recovery. Finally, the status of the project will be reviewed.


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